The Role of Beaver Ponds in Aquatic Ecosystems Impacted by Acid Mine Drainage

Honors Undergraduate Thesis

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Abstract

Acid mine drainage (AMD) is caused when water runs over sulfur-rich rocks that have been exposed during mining activity, causing low pH and high metal contamination in nearby waterways. AMD is an issue affecting aquatic ecosystems worldwide, and current remediation methods are costly and have varying degrees of effectiveness. Beaver ponds have been shown to have mitigating effects on landscapes impacted by acid rain, but little is known about their impacts on aquatic ecosystems affected by AMD. This study found that as a stream in Zanesville, Ohio flowed through a series of beaver ponds, several components of water quality improved. Throughout the stream, pH increased, metal concentrations decreased, conductivity decreased, and leaf decomposition increased. If beaver ponds are capable of mitigating effects of AMD, they could be practical tools for ecosystem restoration across the world. The reintroduction of beavers into landscapes affected by AMD could be less costly than current methods. This project found a preliminary correlation between beaver ponds and improving water quality in AMD streams, while further investigation is needed to see if beaver ponds can restore aquatic ecosystem functioning.

Table of Contents

Introduction: What is Acid Mine Drainage?

Acid mine drainage (AMD) threatens the health of many aquatic ecosystems worldwide. It is a result of mining activity and the processing of metal ores that exposes sulfur-rich rocks to oxygen and water. This causes accelerated oxidation of sulfuric minerals (Johnson & Hallberg, 2005) and results in the formation of sulfuric acid. The acid then contaminates water which flows into nearby waterways and creates a low pH aquatic environment. Many metals are soluble at low pH levels, resulting in the enhanced mobility of heavy metals found in acidic mine water, such as aluminum, iron, and magnesium which also experience weathering reactions (Niyogi et al., 2001). High levels of such metals can be toxic to aquatic organisms. As mine water enters a stream, it is buffered and diluted, which causes metals such as aluminum and iron to precipitate and become deposited on the stream beds (Niyogi et al., 2001). This can harm the detritus-processing organisms in the stream, causing slowdowns of leaf litter processing which causes carbon imbalances that affect ecosystem functioning (Scheiring, 1993).

Acid mine drainage is a complex issue, as it causes altered stream chemistry that is responsible for a cascade of harmful impacts to the surrounding aquatic ecosystem. Some ecological impacts include habitat degradation and niche loss, lower primary productivity, and bioaccumulation of toxic metals within the food chain (Gray, 1997). These toxic metals can cause acute issues, such as death right after exposure, or more chronic issues such as stunted growth and reproductive issues (Simate, 2014). Acid mine drainage can also result in physical changes to the stream, including increased sedimentation and turbidity (Gray, 1997) that can negatively impact stream biota. The wide range of issues that acid mine drainage creates can result in overall negative changes to the community structure and function of impacted streams.

There is a combination of factors impacting the treatment of AMD, including complex hydrology and chemical reactions.

Acid mine drainage also threatens human health, as it contaminates water where people source drinking water from. It also affects areas where recreation such as fishing, swimming, and boating occurs. Many of the components of AMD water are highly toxic to humans. There are certain substances in mining waste that result in soil, air, and water emissions, all of which can harm human health (Hengen et al., 2014). Chronic exposure to those toxic heavy metals from mine waste may cause health issues including cancers, developmental delays, and nervous system damage (Simate, 2014).

Acid Mine Drainage in Ohio

Acid mine drainage is a major issue in many parts of the world. In Ohio alone, there are an estimated 1,300 miles of streams impacted by acid mine drainage (ODNR, 2019). Many of these affected streams are found in Southeastern Ohio, as this area of the state is where the majority of the abandoned coal mines are located (Fig. 1). The state is currently facing increasing threats from AMD, as the shutdown of coal mines across the state continues to occur. Many coal producers are struggling as utility companies transition from coal to cheaper, cleaner renewable energy sources or natural gas (Raby, 2020). For example, Murray Energy, the country's fourth largest coal producer, owns 13 coal mining permits in Ohio. In November 2019, Murray Energy filed for bankruptcy protection (Burger, 2019). While it has since emerged from bankruptcy under a new company, the CEO Robert Moore has recently expressed concern for the future of coal mining, citing the "global pandemic and extremely volatile coal markets" (Raby, 2020). For remediation efforts, the state fund dedicated to mining reclamation only contains $21 million but the state estimates that it would cost around $202 million to reclaim only Murray's sites (Burger, 2019) if they were to be abandoned. As coal mines are shut down across the state, if they are not reclaimed properly it can lead to increased contamination of streams by acidic mining waste.

Acid mine drainage has been an issue for several decades. In 1977, the federal Surface Mining Control and Reclamation Act of 1977 was passed, which is supposed to provide protection against environmental degradation due to mining (Beck, 1995). However, this policy has historically experienced a lack of implementation, likely due to the unwillingness of state agencies to take action towards mining reclamation (Menzel, 1981). In recent years, this law has not been enforced strictly by the federal government as an attempt to rejuvenate the coal industry. As a result of this, more acres of land are being left untreated, resulting in the contamination of more waterbodies by AMD. With the number of streams already impacted by AMD, there is not enough funding available to even attempt to remediate the extent of the damage that the increasing abandoned mining sites will cause.

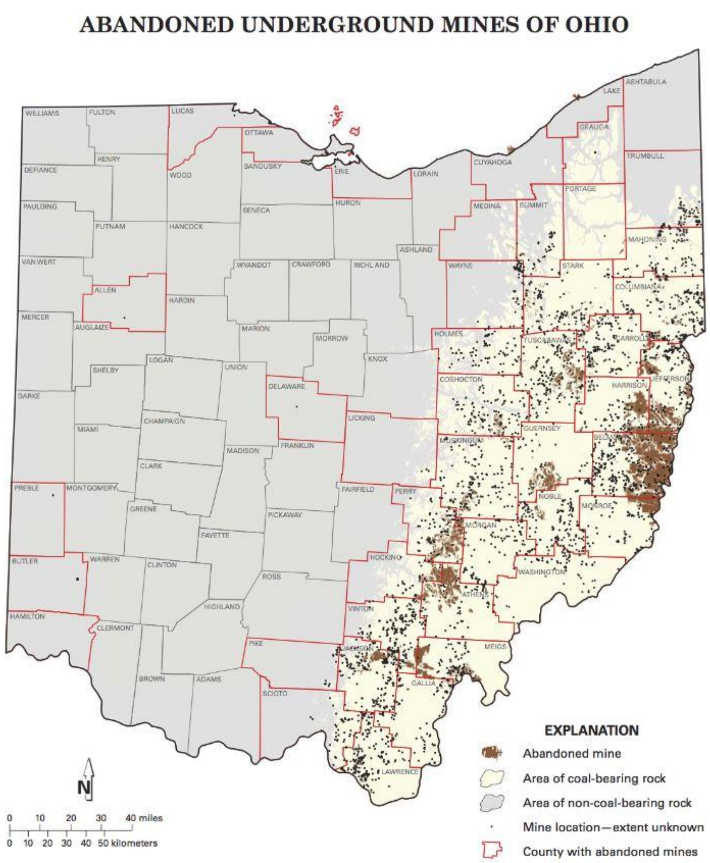

Fig. 1. Locations of abandoned mines in Ohio. (Courtesy of Cleveland.com)

Treatment Methods

The complexity and variation of issues found in AMD ecosystems poses a challenge when considering remediation options. There are typically two approaches used to combat AMD: source control and migration control (Johnson & Hallberg, 2005). Source control focuses on eliminating the source of AMD before it can spread to an ecosystem, and mitigation control involves restoring ecosystems that have already been impacted by AMD. Source control involves processes such as adding a cover, cap, or seal to mining waste to prevent the sulfuric waste from interacting with water or oxygen (Kuyucak, 1999). It is less common than mitigation control because it is only effective if all sources of acidic water are known (Johnson & Hallberg, 2005). Due to the complex nature of AMD, there are not any treatment methods that are completely reliable, efficient, and cost-effective (Kuyucak, 1999).

Currently, most treatment methods are types of migration control. The most common method is adding a source of alkalinity to affected streams such as limestone (Akcil & Koldas, 2006). Raising the pH above the threshold required for iron oxidizing bacteria will reduce the acid generation rate. However, the limestone may become coated with iron or biological growth quickly when it enters the stream, which then prevents any interaction with mine waste (Akcil & Koldas, 2006). This greatly reduces the effectiveness of limestone treatment. Another common treatment method of AMD is to construct a wetland-like treatment pond to hold water while it is being treated with oxidation cells and organic materials (Johnson & Hallberg, 2005). These constructed wetlands are often expensive to install and maintain, and they vary in the degree of their effectiveness (Mays & Edwards, 2001). Acid mine drainage impacts each ecosystem differently and varies in strength and composition seasonally based on how much runoff occurs due to rainfall (Gray, 1997), which makes it harder to predict the most effective type of treatment. Acid mine drainage is a worldwide issue that impacts many types of ecosystems to varying degrees. There is not enough funding available to treat every location impacted by AMD with these costly methods.

Beavers as Ecosystem Engineers

Wetlands have been shown to perform many important ecosystem functions, including flood control, carbon storage, and water filtration. Studies have shown that natural and constructed wetlands can remove heavy metals from water through biological and chemical reactions. They are also inexpensive to maintain and can benefit the biodiversity of the surrounding ecosystem (Dean et al., 2013). Beaver ponds are wetlands constructed by beaver that may provide benefits similar to other wetlands. They are shallow water bodies with low water flow and high residence times, which allows nutrients and other sediments, such as metal precipitates, to settle at the bottom (Correll et al., 2000). Additionally, in studies of landscapes impacted by acid rain, beaver ponds have been found to improve the ability of aquatic ecosystems to neutralize acidic inputs (Cirmo & Driscoll, 1993). They have also been shown to retain organic matter and sediment as well as alter nutrient cycling (Naiman et. al, 1988). These qualities indicate that beaver ponds may provide similar functions to a constructed wetland for streams impacted by AMD.

Given that acid mine drainage is a complex issue and treatment methods are variable in their effectiveness, I focused on the following question for this study: “Do beaver ponds change the water chemistry of a stream impacted by AMD?” I hypothesize that beaver ponds improve the water quality in streams impacted by AMD through changes in water chemistry, including increasing pH and decreasing metal concentrations. The objectives of this study are to first, measure how beaver ponds impact water chemistry of a stream impacted by AMD; and second, to investigate seasonal trends in water chemistry of a stream impacted by AMD. To accomplish this, I analyzed a series of water chemistry parameters throughout a stream and beaver pond network in Zanesville, Ohio to build a chemical profile of an watershed impacted by AMD.

Materials and Methodology

Site Description

The Wilds is a conservation park that was built on old mine land in southeastern Ohio. In the 1950s, coal mining ceased in the northern portion of The Wilds and trees were planted as an attempt at ecosystem restoration. Due to minimal remediation efforts, streams in this area currently experience significant impacts from AMD, with pH values as low as 3-4 and high concentrations of iron, aluminum, and sulfur. According to satellite imagery dating back to 1994, beavers built a series of five ponds in a stream running alongside Watson Road at least 26 years ago (Fig. 2). Two of these ponds, ponds 3 and 4, are nested and connected to each other. Personal observation of these streams showed that upstream of the beaver ponds, there were visible orange and white precipitates of iron and aluminum respectively (Fig. 3), and downstream of the beaver ponds there was no visible evidence of these precipitates. Upstream, leaves in the streams did not exhibit any signs of decomposition or decay. Downstream, leaves were visually more decomposed than the upstream leaves.

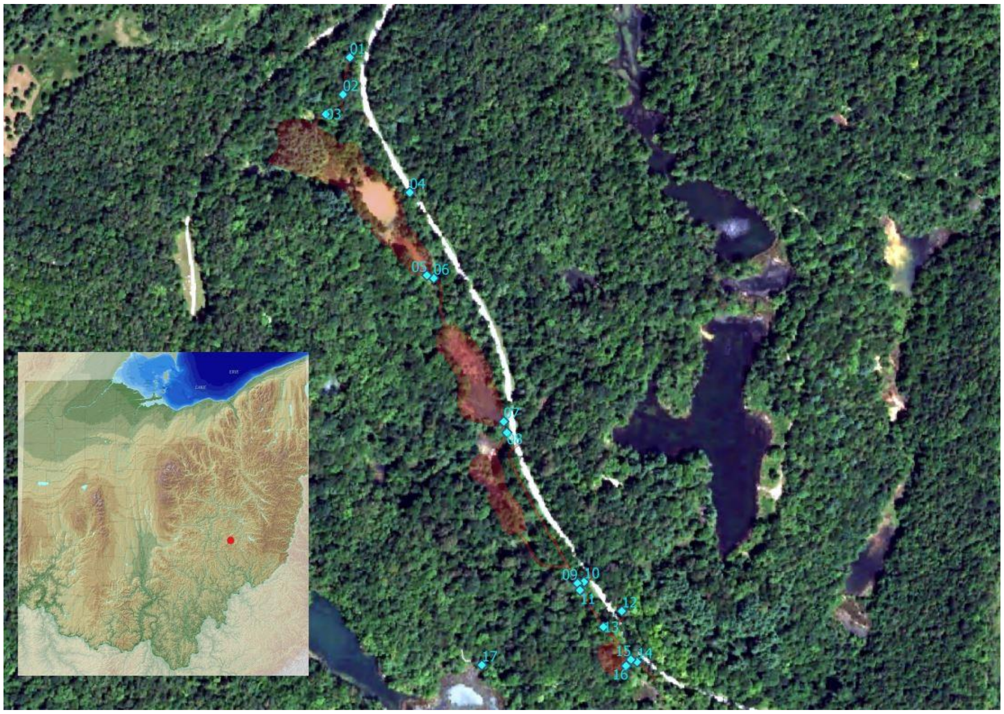

Fig. 2a. A satellite image of the study stream along Watson Road. The inset is the location of the Wilds in Ohio. (Map courtesy of Chris Vogler)

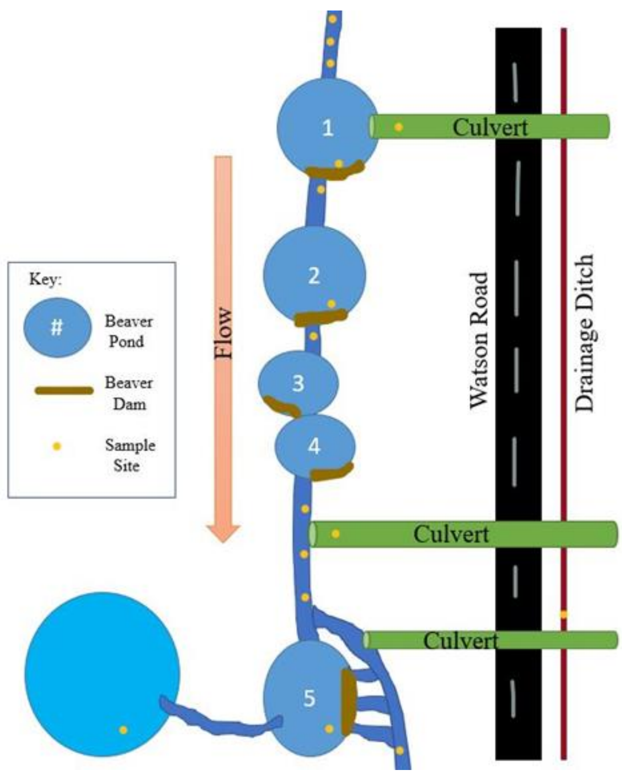

Fig. 2b. A schematic of the location of the beaver ponds in relation to Watson Road, along with sampling sites (not to scale).

Fig. 3. Upstream of the beaver ponds, visible iron and aluminum precipitates are seen in the streambeds and along the banks. (Photos courtesy of Dr. Rachel Gabor)

Sample Collection

We performed synoptic surveys on June 21st, July 25th, September 7th, and November 27th, 2019 to measure water chemistry along the stream. A YSI Sonde was used to collect temperature, pH, conductivity, and dissolved oxygen data in the field. Water samples were collected in LPDE bottles with no headspace. Samples for cations, ions, nutrient, and metal analysis were filtered with 0.45 μm nylon filters. The samples for cation and metal analysis were then acidified with trace metal grade nitric acid and placed in a refrigerator until analyzed. Samples for anion and nutrient analysis were frozen (Gabor et al., 2017).

In summer 2019, leaf litter packs were placed in several locations throughout the stream and in the beaver ponds. They were initially placed to collect macroinvertebrate samples; however, they were instead used as qualitative indicators of leaf decomposition. Leaf decomposition was recorded by visually observing leaf structure in each pack to estimate the degree of processing due to macroinvertebrates that occurred at each site along the stream.

Sample Analysis

Ion chromatography was performed on a Metrohm IC to measure cations (Na^{+}, Mg^{2+}, Ca^{2+}, K^{+}, NH_4^{+}) and anions (Cl^{-}, SO_4^{2-}, PO_4^{3-}, NO_3^{-}, F^{-}). Metal concentration was analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

Results and Discussion

Overview

Water chemistry varied significantly throughout the stream as it flowed through the series of five beaver ponds. Ponds 3 and 4 are henceforth represented as one pond for the results since they are nested and connected to each other. Upstream of the ponds, there was an environment with a low pH, containing high levels of dissolved metals such as iron and aluminum. These metals were introduced through acidic mine waste because they are soluble at low pH levels. Downstream of the ponds, the pH increased, and dissolved contaminants such as sulfur, iron and aluminum decreased. There were also visible differences in leaf decomposition observed above and below the beaver ponds. Some seasonal variation between summer and fall was observed with pH and conductivity. pH levels were generally lower in the summer months and higher in the fall months, while conductivity was higher in the summer and lower in the fall. Overall, water quality improved throughout the stream as it moved through the ponds with regards to an increase in pH, a decrease in dissolved metal concentrations, and a qualitative increase in leaf decomposition.

Stream pH

The pH of the stream water generally increased as the stream flowed through the beaver ponds, with some spatial fluctuations and seasonal variation (Fig. 4). The stream was sampled at three locations upstream of the first beaver pond, with the first site located 100 m above the start of the pond. In this segment, the pH of the furthest upstream site ranged from 3.4-4.4 and increased to 4.2-4.7 before entering pond 1. After flowing through the beaver ponds, 770 m from the furthest upstream site, the stream pH increased to 6.3-7.6, with some variation along the way. Specifically, in pond 2, the pH was consistently lower at the outlet than the inlet, but in pond 4 the pH was higher at the outlet than the inlet. Additionally, downstream of the fourth pond, a culvert with bright orange water and a pH from 3.9-4.6 flowed into the stream. A slight drop in pH was observed immediately downstream of the culvert, decreasing from 6.1-7.1 above the culvert to 5.1-5.9 below it, but it quickly began increasing again. Overall, within the 800 m reach of stream, the pH rose from 3.3 to 7.6.

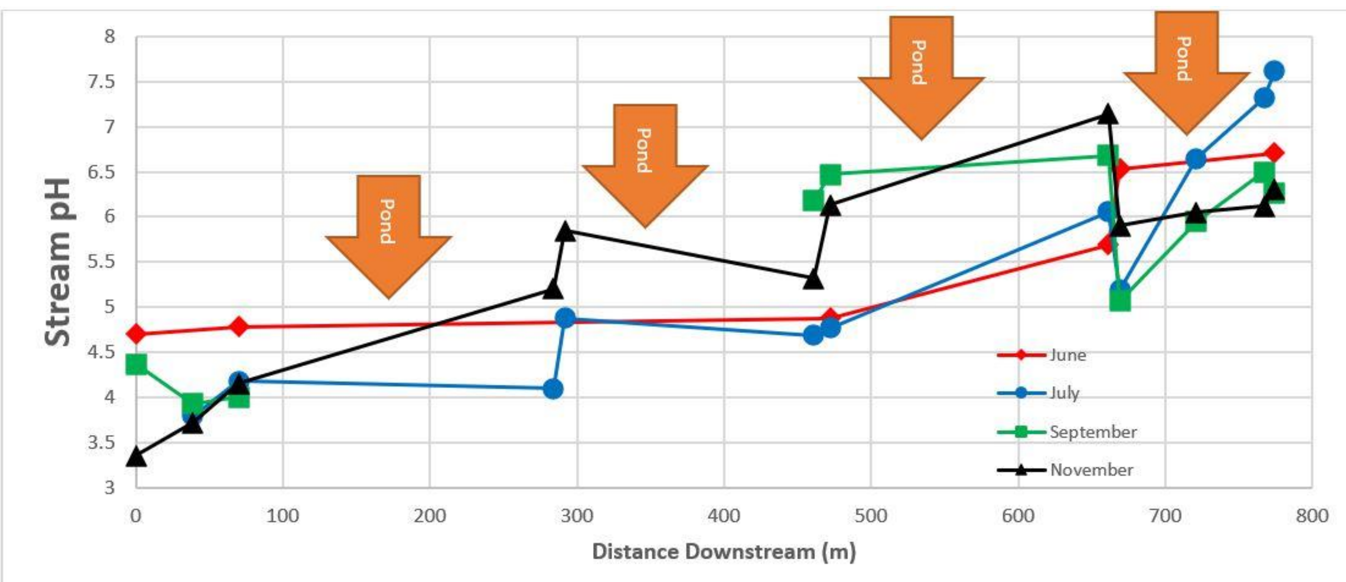

Fig. 4. pH trends throughout the stream.

Some seasonal variation occurred with pH. In September and November, the pH was generally higher at most of the sites, while in June and July it was lower. pH may be impacted by water temperature changes since lower pH values are associated with warmer water, but it is likely not the main factor behind the differences. The water table in the summer and fall may be at different heights and different volumes of groundwater are entering the stream each season. If there is more groundwater coming into the stream, the stream chemistry will be closer to the groundwater than the stream flow. Additionally, precipitation may impact stream pH. In Ohio, it often rains more in the fall than in the summer. In the fall months, pH was higher, and this may be due to more inputs of rainwater that could have a higher pH than the streamflow.

Streams naturally experience some amount of buffering due to the presence of calcium and magnesium within the bedrock and soil of the streambed. Calcium is found in streams largely as calcium carbonate, which dissolves more readily in acidic water. As it dissolves, the carbonate pulls hydrogen ions out of the water to form bicarbonate. Higher levels of bicarbonate helps streams to resist pH changes from acidic inputs, such as mine drainage. In this study, calcium and magnesium both decreased throughout the reach as the stream became less acidic and more neutral. pH trends were not entirely consistent, as the pH increased after pond 1 but dropped after pond 2. This indicates there may be factors within each pond impacting the change in pH, such as sediment composition and residence time. Additionally, pH climbed before entering the first pond which indicates the buffering ability of the stream, likely due to the high concentrations of calcium seen upstream of the ponds. Overall, pH appeared to be impacted by the presence of beaver ponds, but there are multiple factors influencing the stream pH including the acidic inputs, such as culverts, seen along the reach. Groundwater also may influence pH, as it is unknown if it is more or less acidic than the stream discharge.

Conductivity and Ions

Conductivity decreased in general as the stream flowed through the beaver ponds. (Fig. 5). Above the ponds at the furthest upstream site, conductivity was the highest, ranging between 3450-2880 µS/cm before entering pond 1. After flowing through pond 1, the conductivity of the stream decreased steadily until it reached the outlet of pond 2. From the outlet of pond 2 to the outlet of pond 4, the conductivity increased slightly, before dropping again. After flowing through the final pond, conductivity decreased to 1784-2389 µS/cm.

Along with conductivity, ion concentrations showed a corresponding decrease as the stream flowed through the ponds. Sulfate showed the most significant decrease (Fig. 5) with trends remaining very similar throughout each season. As with conductivity, sulfate was the highest upstream of pond 1, ranging from 2560-2960 mg/L. It decreased steadily until it reached the outlet of pond 2. It increased from the outlet of pond 2 until the outlet of pond 4, before decreasing again at the outlet of pond 5. Downstream of pond 5, sulfate was the lowest, showing a concentration of 1530-1538 mg/L.

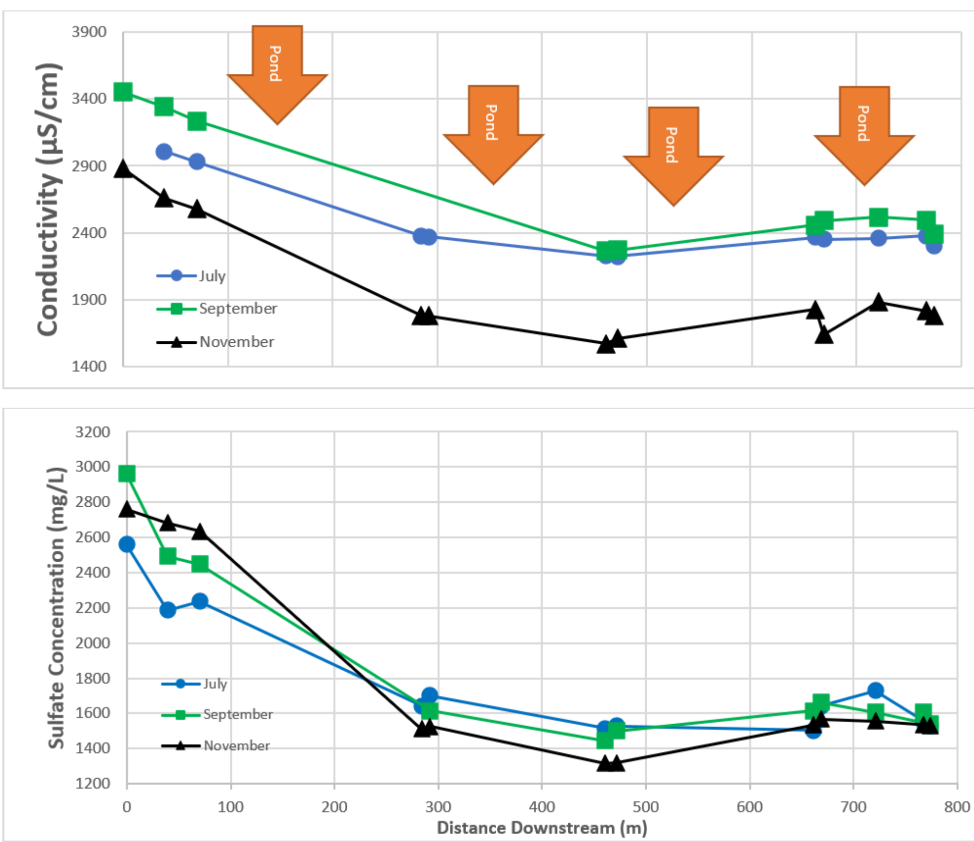

Fig. 5. Conductivity and sulfate patterns.

Calcium and magnesium were the second and third highest ions measured, but they decreased much less than sulfate. Calcium measured from 412-446 mg/L upstream of the ponds and decreased to 313-359 mg/L downstream of pond 5, while magnesium measured 178-217 mg/L upstream and dropped to 145-165 mg/L downstream of pond 5 (Fig. 6).

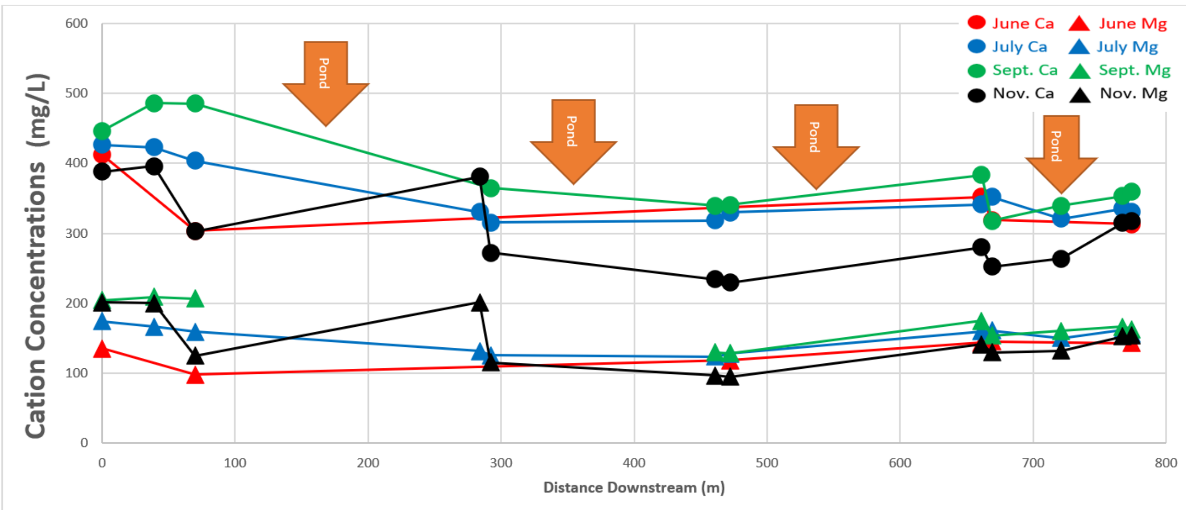

Fig. 6. Calcium and magnesium concentrations.

Some seasonal variation occurred with conductivity. While the trends remained very similar, values for conductivity were generally lowest in November. Values were similar in July and September, with September peaking slightly higher than July. Little to no seasonal variation occurred with sulfate, calcium, and magnesium concentrations. Conductivity can be affected by changes in water temperature; however, it is likely not the main reason for the decrease seen throughout the stream. Conductivity measures the ability of water to conduct an electrical current and is impacted by the presence of ions. It can be affected by the geology of the bedrock found under the stream, as it impacts the levels of calcium and magnesium seen in the stream. It is also affected by mining waste since it is rich in dissolved ions. The ion with the highest concentration found in the stream was sulfate, and it showed a notable decrease in concentration throughout the stream. Since the decrease in sulfate correlated largely with the decrease in conductivity, it was likely the biggest driver behind the decrease in conductivity.

Concentrations of Dissolved Metals

In general, concentrations of iron and aluminum decreased as the stream flowed through the ponds (Fig. 7). Upstream of the ponds, the concentration of iron in the stream decreased significantly before even entering pond 1. At the furthest upstream site, the iron concentration was 48.3 mg/L, and it dropped to 9.7 mg/L before it entered pond 1. There were visible bright orange precipitates in this entire section of stream. A culvert with an iron concentration of 12.3 mg/L flowed into the middle of pond 1, but after flowing through pond 1 and pond 2 the iron concentration of the stream dropped to 0.40 mg/L, indicating little impact from the iron-rich culvert. After flowing through pond 5, the iron concentration decreased again to 0.31 mg/L.

Aluminum experienced similar trends. Above the first pond, at the furthest upstream site the concentration was 85.1 mg/L, and it decreased slightly to 55.5 mg/L before entering pond 1. After pond 2, the aluminum concentration decreased much more significantly, dropping to 5.8 mg/L. After flowing through pond 5, aluminum concentrations were below the detection limit of 4.9 mg/L.

Iron precipitates at pH > 3.5. This may account for the decrease in iron seen above pond 1, since a thick layer of orange iron precipitate was visible along the stream bed. As mining waste with high concentrations of dissolved iron enters the stream, it will precipitate out once the pH reaches 3.5, which happened before reaching pond 1. Aluminum precipitates at pH > 5. After flowing through pond 2, the stream pH remained mostly above 5. Additionally, within pond 2, there were visible white precipitates, which may account for the drop in dissolved aluminum after this pond.

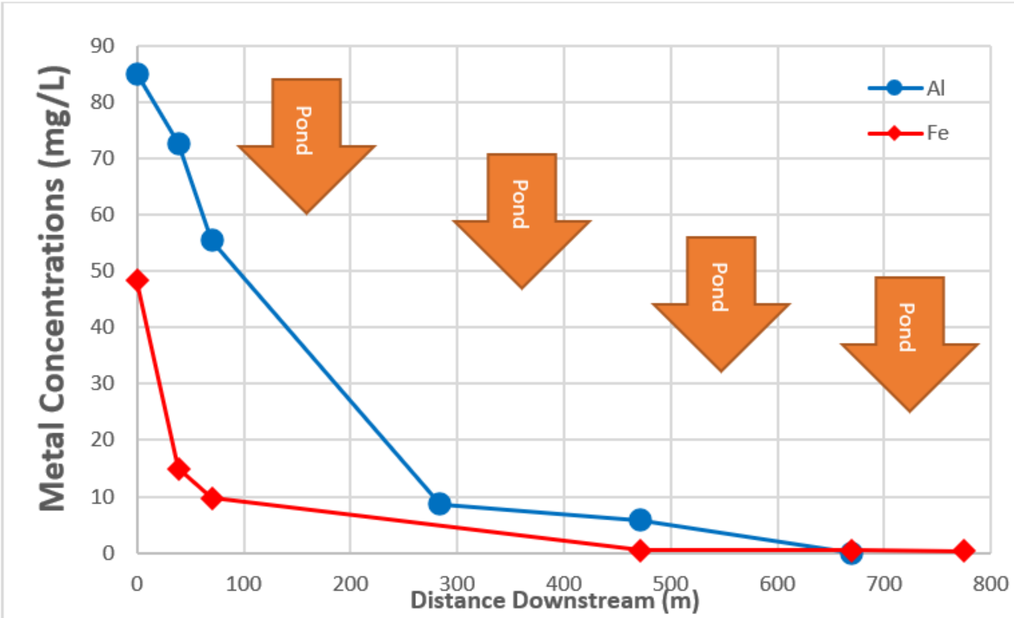

Fig. 7. Aluminum and iron concentrations from June.

Leaf Decomposition and Nutrients

Leaf litter packs were placed initially to quantify the macroinvertebrates that colonized the packs. Upon analysis of the packs, very few macroinvertebrates were found within the packs. Leaf decomposition was observed qualitatively by inspecting the leaf litter packs after 8 weeks of being submerged in the stream. Upstream of the beaver ponds, leaves were left almost untouched, with no visible decomposition. The leaves were whole and did not appear shredded or broken down to any extent, and they were coated in a thick layer of orange iron precipitate. Downstream of the ponds, leaves were visibly decomposed, with smaller pieces present. The leaf structure was less recognizable, as they had been broken down into finer matter.

Nutrients in the stream, including phosphorous and nitrate, were consistently low and did not change significantly throughout the stream. Phosphorous was negligible through the whole stream. Nitrate ranged from 0-0.4 mg/L with no consistent trends seen upstream or downstream of the ponds.

The lack of leaf decomposition observed upstream of the ponds indicates low activity from macroinvertebrates and microbes. Many aquatic species are intolerant of environments with low pH conditions and high metal concentrations, which results in low or no insect colonization of the upstream habitat. Low nutrient availability results in a lack in growth of algae or other aquatic primary producers, which suggests a stream with low productivity.

Drivers of Changes in Water Chemistry

Several changes in water chemistry occurred throughout the 800 m stream reach. This included increasing pH, decreasing conductivity, sulfate, magnesium, and calcium concentrations, decreasing metal concentrations, and increasing leaf decomposition. While it is apparent that water quality increased with movement downstream, there are multiple explanations and factors as to what may be driving the changes in water chemistry. Within the beaver ponds, there was not a consistent trend in pH changes. Some ponds experienced an increase in pH from the input the output, while some experienced a decrease. There are complex biological and chemical reactions that occur in ponds that may impact pH by pulling hydrogen ions out of the water. Additionally, the sediment composition at the bottom of the ponds may impact the chemistry of the water. Different amounts of sulfate-reducing bacteria may be present within each pond. When metals precipitate out of the water in the ponds, it is likely that they settle at the bottom of those ponds. The pH of each pond influences if metals will precipitate out or not, so a more acidic pond will see higher levels of dissolved metals when compared to a less acidic pond. Residence time also plays a factor in driving water chemistry changes, as how long each pond holds water may affect the pH as it remains in the pond. The longer it remains in the pond, the more time there is for such reactions to occur that are drivers of changes in pH.

Conclusion

The impact of acid mine drainage on stream water quality is a complex issue. Acid mine drainage can degrade aquatic ecosystems of the receiving streams by lowering the pH, increasing concentrations of metals, and decreasing leaf processing. This study stream exhibited those qualities upstream of the beaver ponds. As the study stream flowed through the series of beaver ponds, water quality improved as measured by increasing pH, decreasing metal concentrations, and increased leaf decomposition. In past studies, beaver ponds have been shown to improve the ability of aquatic ecosystems to recover from inputs of acidic rain (Cirmo & Driscoll, 1993). At this site we observed that mining waste was an acidic input to this stream that appeared to be neutralized by the presence of beaver ponds.

Few studies of the interactions between beaver ponds and AMD have been published. One study that was recently done assessed water chemistry of a stream and beaver pond network in Northeastern Ohio that is impacted by AMD. Their data showed that water upstream of the beaver dams was of higher quality than that below it by a measure of decreasing pH and increasing metal concentrations (Shaw et al., 2020) which is opposite of the trends exhibited by the Watson Road stream. This difference in results between two studies indicates that further research is needed to assess the impacts of beaver ponds on AMD stream water quality.

The results of this study indicate that water quality improved through the series of ponds, but the results do not address if ecosystem functioning is improved downstream of the ponds in comparison to upstream. An increase in water quality is just one measurement of ecosystem restoration. Future work is needed to address if ecosystem functioning of the AMD stream is being restored by the series of beaver ponds.

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